Small Signal Stability Improvement and Congestion Management Using PSO Based TCSC Controller

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***Abstract*— In this paper an attempt has been made to study the application of Thyristor Controlled Series Capacitor (TCSC) to mitigate small signal stability problem in addition to congestion management of a heavily loaded line in a multimachine power system. The Flexible AC Transmission System (FACTS) devices such as TCSC can be used to control the power flows in the network and can help in improvement of small signal stability aspect. It can also provide relief to congestion in the heavily loaded line. However, the performance of any FACTS device highly depends upon its parameters and placement at suitable locations in the power network. In this paper, Particle Swarm Optimization (PSO) method has been used for determining the optimal locations and parameters of the TCSC controller in order to damp small signal oscillations. Transmission Line Flow (TLF) Sensitivity method has been used for curtailment of non-firm load to limit power flow congestion. The results of simulation reveals that TCSC controllers, placed optimally, not only mitigate small signal oscillations but they can also alleviate line flow congestion effectively.**

***Keywords*—Congestion management, Particle Swarm Optimization, Small Signal Stability, Thyristor Controlled Series Compensator, Transmission Line Flow Sensitivity.**

I. Introduction

In deregulated power industry congestion occurs more frequently on many individual transmission systems when contingency or load increase happens in power system and it may even cause some physical violations such as transmission line overload or low/high bus voltage profile in the system. In these cases, it may be needed to shed some load to ensure that transmission overload security limits are satisfied. The development of FACTS has potential contribution on load curtailment issues [1]. Thyristor Controlled Series Compensator (TCSC) is a series controlled device in the FACTS family that are increasingly applied for this purpose in long transmission lines in modern power systems [2]. In [3] TCSC and SVC were used as re-dispatch tools for congestion management with Total Transfer Capability (TTC) improvement.

Another challenging problem to the researcher in modern power industry is the low frequency power oscillations. Traditionally [4], Power System Stabilizers (PSS) have been employed as the first choice to mitigate these problems. However, performance of PSS gets affected by network configurations, load variations etc. Hence installations of FACTS devices have been suggested in this paper to achieve appreciable damping of system oscillations.

But when TCSC has been installed at different locations, its performance and effect is different. It is important to locate TCSC devices at suitable place in the transmission network to achieve desired objectives. The optimal allocation of TCSC has been reported in literatures [5]-[7] based on many aspects - optimal power flow (OPF) with lowest cost generation, reactive power planning, etc. In this paper the TCSC has been used for small signal stability improvement and a novel stochastic method, Particle Swarm Optimization [8] has been implemented for finding the optimal location and parameters of the TCSC controller. Though PSO has been employed in several research papers [9]-[10] for the design of optimal FACTS controllers, the applications are mostly limited to the case of single machine infinite bus system.

In this paper the application of TCSC controller has been extended to study the small signal oscillation problem in case of a multimachine power system and a novel use of TCSC has been explored for transmission overload curtailment and congestion management. Transmission Line Flow (TLF) sensitivity values for the most overloaded line have been considered for calculating the necessary load curtailment for the alleviation of the transmission congestion.

The paper has been organized as follows: section II describes the definition and method of (TLF sensitivity based) congestion managements. The small signal modeling of the multimachine system working with TCSC controllers has been represented in section III. In section IV the general theory of PSO and the proposed optimization problem has been discussed. The impact of TCSC on load curtailment has been examined in section V. The PSO algorithm has been implemented in the section V to determine optimal location and parameters of the TCSC controller. The validity of the proposed methods have been tested in a 3-machine, 9-bus system.

II. Congestion management

A. Definition of Congestion Management

When the producer and consumer of electric energy desire

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to produce and consume an amount of electric energy, the transmission system may operate at or beyond one or more transfer limits and the system is said to be congested. In heavily congested conditions, transmission congestion can be relieved by curtailing a portion of non-firm transactions. An example of two-bus system has been shown in Fig. 1 to explain transmission congestion.

In Fig. 1(a), the maximum real power output of the machine is 60 MW, the transmission line flow limit is 55 MW and the load is 58 MW. Therefore, there is a transmission overload in the transmission line to serve the load. Congestion can be alleviated by curtailing some portion of the load. In Fig. 1(b), the load has been curtailed from 58 MW to 54 MW and the congestion has been alleviated.

B. Methods of Congestion Management

The power flow P_{ij} through the transmission line ***i-j*** is a function of the line reactance X_{ij}, the voltage magnitudes V_i, V_j and the phase angle ($\delta_i - \delta_j$) between the sending and receiving end voltages (,) as shown in equation (1).

$$P_{ij} = \frac{V_i V_j}{X_{ij}} \sin(\delta_i - \delta_j) \tag{1}$$

From equation (1), it has been seen that the power flow can be affected with the change of voltage magnitudes, the reactance of the transmission lines or the power angle (). It has been well established that voltage magnitudes can be controlled through VAR support. The reactance of the line can be reduced through series compensation and the power angle can be varied via power injection changes at either bus, e.g. generation or load changes. In this paper, series compensation of line reactance has been considered for congestion management and TLF sensitivity (sensitivities of the line flows to load change) value for the most overloaded line has been considered for calculating the necessary load curtailment.

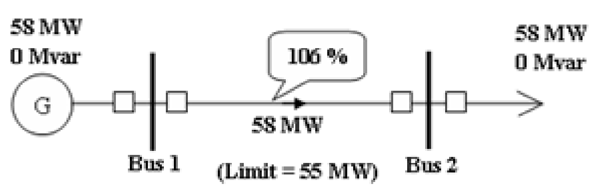

Fig. 1(a) Two-bus system with congestion

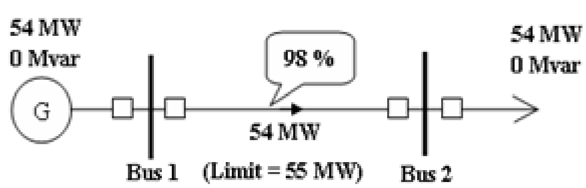

Fig. 1(b) Two-bus system with congestion alleviated

The TLF sensitivity at a bus *k* due to change load power ΔP_k for a congested line ***i-j*** is T_{ij}^k and has been calculated using the relation shown in equation (2)

$$T_{ij}^k = \frac{\Delta S_{ij}}{\Delta P_k} \tag{2}$$

The load curtailment at bus *k* can be obtained as

$$P_k^{cut} = \frac{T_{ij}^k}{\sum_N T_{ij}^k} \overline{\Delta S_{ij}} \tag{3}$$

where $\overline{\Delta S_{ij}} = S_{ij} - \overline{S_{ij}}$

S_{ij} : Actual power flow through transmission line ***i-j***

$\overline{S_{ij}}$: Flow limit of transmission line ***i-j***

N : Total numbers of branches between load buses.

The higher the TLF sensitivity the more is the effect of a single MW power transfer at any bus. Hence, based on the TLF sensitivity values the loads are curtailed in required amounts at the load buses in order to eliminate the transmission congestion on the congested line ***i-j***.

III. Small signal modeling

A. Modeling of TCSC

The basic TCSC module and the transfer function model of a TCSC controller [11] have been shown in Fig. 2(a) and 2(b) respectively. This simple model utilizes the concept of a variable series reactance which can be adjusted through appropriate variation of the firing angle (α). The controller comprises of a gain block, a signal washout block and a phase compensator block. The input signal is the normalized speed deviation (Δv), and output signal is the stabilizing signal (i.e. deviation in conduction angle, $\Delta\sigma$).

Neglecting washout stage, the TCSC controller model can be represented by the following state equations;

$$\Delta\dot{\alpha} = -\frac{1}{T_2}\Delta\alpha - \frac{K_{tcsc}}{\omega_s}\left(\frac{1}{T_2}\right)\Delta\omega - \frac{K_{tcsc}}{\omega_s}\left(\frac{T_1}{T_2}\right)\Delta\dot{\omega} \tag{4}$$

$$\Delta\dot{X}_{tcsc} = -\frac{1}{T_{tcsc}}\Delta\alpha - \frac{1}{T_{tcsc}}\Delta X_{tcsc} \tag{5}$$

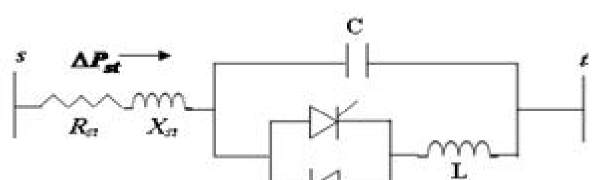

Fig. 2(a) TCSC module

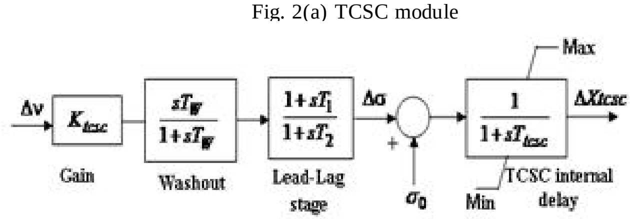

Fig. 2(b) Structure of a TCSC based controller

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The steady-state relationship between the firing angle α and the equivalent TCSC reactance, X_{tcsc} is given by [12]

$$X_{tcsc} = -X_C + C_1(2(\pi-\alpha) + \sin(2(\pi-\alpha))) - C_2\cos^2(\pi-\alpha)(\varpi\tan(\varpi(\pi-\alpha)) - \tan(\pi-\alpha)) \quad (6)$$

where $X_{LC} = \dfrac{X_C X_L}{X_C - X_L}$, $\quad C_1 = \dfrac{X_C + X_{LC}}{\pi}$

and $C_2 = \dfrac{4X_{LC}^2}{\pi X_L}$. The linearized TCSC equivalent reactance can be obtained from (6) is

$$\Delta X_{TCSC} = \Big\{-2C_1(1+\cos(2\alpha)) + C_2\sin(2\alpha)(\varpi\tan(\varpi(\pi-\alpha)) - \tan\alpha) + C_2\left(\varpi^2\frac{\cos^2(\pi-\alpha)}{\cos^2(\varpi(\pi-\alpha))} - 1\right)\Big\}\Delta\alpha \quad (7)$$

B. Multimachine model with TCSC

The general theory of the small signal stability problem in case of a multimachine system and its linearized model has been described in [13] and is given by

$$\Delta\dot{X} = A_1\Delta X + B_1\Delta I_g + B_2\Delta V_g + E_1\Delta U \quad (8)$$

$$0 = C_1\Delta X + D_1\Delta I_g + D_2\Delta Vg \quad (9)$$

$$0 = C_2\Delta X + D_3\Delta I_g + D_4\Delta V_g + D_5\Delta V_l \quad (10)$$

$$0 = D_6\Delta V_g + D_7\Delta V_l \quad (11)$$

The multimachine linearized model with TCSC controller can be formulated separately by adding the state variables $\Delta x_{tcsc} = [\Delta\alpha \quad \Delta X_{tcsc}]^T$ corresponding to the TCSC controller in equations (8)-(10) and the TCSC power flow equation in the network equation (11).

The TCSC linearized real power flow equation between bus *s* and *t* can be obtained from the following equation

$$\Delta P_{st} = \frac{\partial P_{st}}{\partial\theta_s}\Delta\theta_s + \frac{\partial P_{st}}{\partial V_s}\Delta V_s + \frac{\partial P_{st}}{\partial\theta_t}\Delta\theta_t + \frac{\partial P_{st}}{\partial V_t}\Delta V_t + \frac{\partial P_{st}}{\partial\alpha}\Delta\alpha \quad (12)$$

where, $P_{st} = V_s^2 g_{st} - V_s V_t(g_{st}\cos\delta_{st} + b_{st}\sin\delta_{st}) \quad (13)$

and $Y_{st}^* = \dfrac{1}{R_{st} + j(X_{st} - X_{tcsc})} = \dfrac{R_{st} + j(X_{st} + X_{tcsc})}{R_{st}^2 + (X_{st} + X_{tcsc})^2}$

$$= g_{st} - jb_{st} \quad (14)$$

with $\dfrac{\partial P_s}{\partial\alpha} = -\dfrac{\partial P_{st}}{\partial\alpha}$

$$= -V_s^2\frac{\partial}{\partial\alpha}g_{st} + V_s V_t\left(\cos\delta_{st}\frac{\partial}{\partial\alpha}g_{st} + \sin\delta_{st}\frac{\partial}{\partial\alpha}b_{st}\right) \quad (15)$$

Eliminating ΔI_g from the respective equations (8)-(11), the overall system matrix with TCSC controller can be obtained as

$$[A_{tcsc}]_{(7m+2)\times(7m+2)} = [A''] - [B''][D'']^{-1}[C''] \quad (16)$$

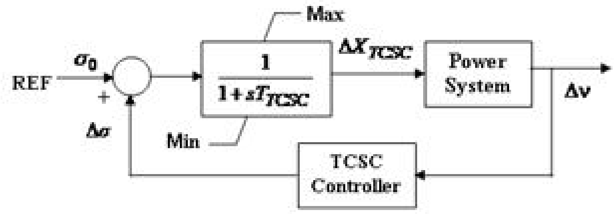

Fig. 3 Block-diagram: Power System with TCSC controller

The block-diagram of the power system with TCSC as a feedback controller has been depicted in Fig. 3.

IV. Formulation of Optimization Problem

A.Particle Swarm Optimization (PSO)

Particle Swarm Optimization was first developed in 1995 by Eberhart and Kennedy [8]. The PSO algorithm begins by initializing a random swarm of *M* particles, each having *R* unknown parameters to be optimized. At each iteration, the fitness of each particle has been evaluated according to the selected fitness function. The algorithm stores and progressively replaces the best fit parameters of each particle ($pbest_i$, i=1, 2, 3, . . . , *M*) as well as a single most fit particle (*gbest*) among all the particles in the group. The parameters of each particle (p_i) in the swarm are updated in each iteration (*n*) according to the following equations:

$$\overline{vel_i}(n) = w\times\overline{vel_i}(n-1) + acc_1\times rand_1\times(gbest - p_i(n-1)) + acc_2\times rand_2\times(pbest_i - p_i(n-1)) \quad (17)$$

$$p_i(n) = p_i(n-1) + \overline{vel_i}(n) \quad (18)$$

where, $vel_i(n)$ is the velocity vector of particle *i* and is a vector of random values $\in(0,1)$. acc_1, acc_2 are the acceleration coefficients that pull each particle towards *gbest* and $pbest_i$ positions respectively and are often set to be 2.0. w is the inertia weight of values $\in(0,1)$. rand_1 and rand_2 are two uniformly distributed random numbers in the ranges [0, 1].

B. Objective Function and Optimization Problem

The problem is to search the optimal location and the parameter set of the TCSC controller using PSO algorithm. The objective is to maximize the damping ratio (ζ) as much as possible. This results in minimization of the critical damping index (*CDI*) given by

$$CDI = J = (1 - |\zeta_i|) \quad (19)$$

Here, ζ_i is the damping ratio of the *i*-th critical swing mode. There are four unknown parameters: the TCSC controllers gain (K_{tcsc}), lead time (T_1), the lag time (T_2) constants and

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TCSC location number (N_{loc}). These parameters have to be optimized by minimizing the objective function J given by the equation (19). With a change of location and the parameters of the TCSC controller, the damping ratio (ζ) as well as J varies.

The optimization problem can then be formulated as:

Minimize J [Equation (19)]

S. T. :

Equality Constraints

$$P_{Gi} - P_{Li} - \sum_{k=1}^{n} V_i V_k Y_{ik}(X_{tcsc})\cos(\theta_i - \theta_k - \gamma_{ik}) = 0 \quad (20)$$

$$Q_{Gi} - Q_{Li} - \sum_{k=1}^{n} V_i V_k Y_{ik}(X_{tcsc})\sin(\theta_i - \theta_k - \gamma_{ik}) = 0 \quad (21)$$

Inequality constraints

$$|(V_i - 1)| \le 0.05$$

$$P_{Gi}^{min} \le P_G \le P_{Gi}^{max} \quad ; \quad Q_{Gi}^{min} \le Q_G \le Q_{Gi}^{max}$$

$$K_{tcsc}^{min} \le K_{tcsc} \le K_{tcsc}^{max} \quad ; \quad T_1^{min} \le T_1 \le T_1^{max}$$

$$T_2^{min} \le T_2 \le T_2^{max} \quad ; \quad N_{loc}^{min} \le N_{loc} \le N_{loc}^{max}$$

C. Particle configuration

The particle can be defined as a vector which contains the TCSC controller parameters and the location number: K_{tcsc}, T_1, T_2 and N_{loc} as shown in equation (22)

$$\textit{Particle}: [K_{tcsc} \quad T_1 \quad T_2 \quad N_{loc}] \quad (22)$$

The particle configurations corresponding to the TCSC controller has been shown in Fig 4. The initial population has been generated randomly for each particle and are kept within a typical range.

To optimize equation (19), routines from PSO toolbox [14] have been used. The objective function corresponding to each particle has been evaluated by small signal analysis program of the proposed test system (Fig. 5). This system has been widely used in literature [13] for small signal stability analysis in power systems. The network branches (line # 4, 5, 6, 7, 8 and 9) between two load buses are selected here for locating the TCSC module and therefore, line #4 and line #9 are given as $N_{loc}^{\min}$ and $N_{loc}^{\max}$ respectively.

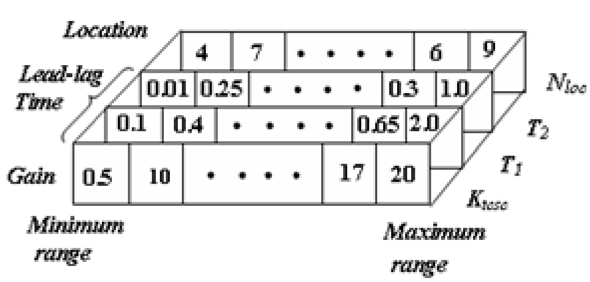

Fig. 4 Particle configuration for TCSC controller

V. Application and Results

A. Application of TLF sensitivity on Load Curtailment

This section describes first the transaction curtailment result using TLF sensitivity procedures, and then the results obtained along with the application of TCSC in the proposed system. Suppose maximum output of all the generators are 250 MW. The real load increased at bus 5 is 50 % more than the base load.

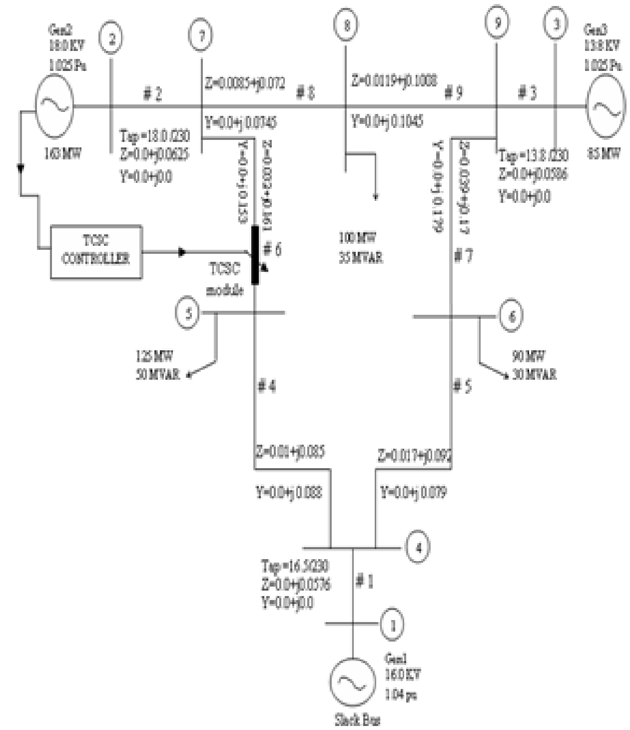

Fig. 5 3-machine, 9-bus system with the application of TCSC

It is assumed that the flow limits of lines # 4, 5 and 9 as 70 MW and for the lines # 6, #7 and 8 as 100 MW, execution of power flow calculation (Table I) revealed that the line # 4 is congested as the real power flow through this line is 85.44 MW which has exceeded its proposed flow limit of 70MW. Therefore, some transaction must be curtailed to avoid congestion in order to maintain the safety of the system. Applying TLF sensitivity procedure, the required amount of load curtailment is obtained as 17.12 MW (Appendix A.2).

After installation of TCSC it has been found that the amount of load curtailment is significantly reduced and the effect is different for different locations of the TCSC module (Table II). In this stage therefore, it may be essential to choose a suitable installing location of the TCSC controller. The optimal location of TCSC can be determined based on different factors such as the stability of the system, the load pattern of the system, the type of contingencies etc. In the following section the issue of small signal stability problem has been considered to identify the optimal location of the TCSC controller.

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TABLE I. POWER FLOW AFTER LOAD INCREASE WITHOUT TCSC

Load Bus	Real Load (P_L) (MW)	Line	Real Power Flow (S) (MW)	Excess Flow ($\overline{\Delta S}$) (MW)
4	0	# 4(4-5)	85.44	15.44
5	187.5	# 5(4-6)	33.46	0.0
6	90	# 6(5-7)	-85.52	0.0
7	0	# 7(6-9)	-47.41	0.0
8	100	# 8(7-8)	64.95	0.0
9	0	# 9(8-9)	-28.04	0.0

TABLE II. POWER FLOW AFTER INSTALLATION OF TCSC

TCSC installed in Line	Power flow (S) in congested line #4 (MW)	Excess flow ($\overline{\Delta S}$) in line #4 (MW)	Load curtail ment (MW)	Improv ement (%)
# 4	53.31	0.0	0.0	100
# 5	81.58	11.58	35.64	0.0
# 6	68.51	0.0	0.0	100
# 7	78.11	8.11	12.73	25.64
# 8	80.92	10.92	13.08	23.59
# 9	81.90	11.90	10.09	41.06

The results obtained in Table II indicate that when TCSC has been installed in line # 6 power flow through the congested line # 4 is well below its flow limit (70 MW) and the required amount of load curtailment in the over loaded bus 5 is zero. This implies that installation of TCSC in line # 6 alleviated power flow congestion 100 % in the congested line # 4 without curtailment of any load.

B. Application of PSO and Small Signal Stability Analysis

In this section the validity of the proposed PSO algorithm has been tested on a 3-machine 9-bus system (Fig. 5). The complex eigenvalues of the system with and without TCSC dynamics are listed in Table III. It has been observed that without TCSC dynamics the electromechanical mode #1 is the critical one as the damping ratio of this mode is smallest compared to other modes. Therefore, stabilization of this mode is essential in order to improve small signal stability. The PSO algorithm (Fig. 6) generates the optimal location and the optimal values of the TCSC controller parameters simultaneously by minimizing the desired objective function *J* and the results are represented in Table IV. The convergence rate of objective function *J* for *gbest* with the number of generations for 200 has been shown in Fig. 7.

It is evident form Table IV that the application of PSO based TCSC controller in its optimal location (line # 6) improved the damping ratio of the critical swing mode # 1 about 33% over the damping ratio without TCSC controller. In view of the results obtained in Table II and Table IV it may be reasonable to conclude that the line #6 is the best location of the TCSC controller.

TABLE III. EIGENVALUES WITHOUT AND WITH TCSC

#	without TCSC	with PSO based TCSC
1	-2.5177 ± j7.0984	-2.7223 ± j5.4908
2	-4.4994 ± j9.2309	-4.5356 ± j10.210
3	-5.8631 ± j7.9134	-6.1060 ± j7.7285
4	-5.2370 ± j7.8298	-5.1524 ± j7.7984
5	-5.4714 ± j7.8523	-5.0390 ± j8.0207
6	-0.4724 ± j1.2409	-0.4516 ± j1.2264
7	-0.4813 ± j0.8068	-0.5341± j0.9445
8	-0.5236 ± j0.5864	-0.5407 ± j0.5843

TABLE IV. PSO BASED TCSC PARAMETERS AND LOCATION

PSO based TCSC parameter	PSO based TCSC location	Damping ratio of critical mode #1	
		without TCSC	with PSO based TCSC
K_{TCSC} = 13.05	N_{loc}= 6	0.3343	0.4442
T_1 = 2.0			
T_2 = 0.2668			

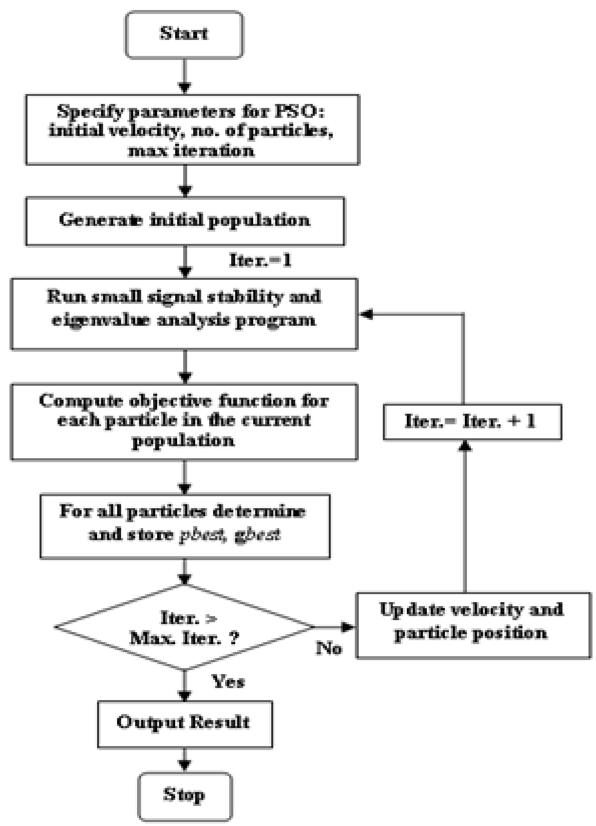

Fig. 6 Algorithm of the implemented PSO

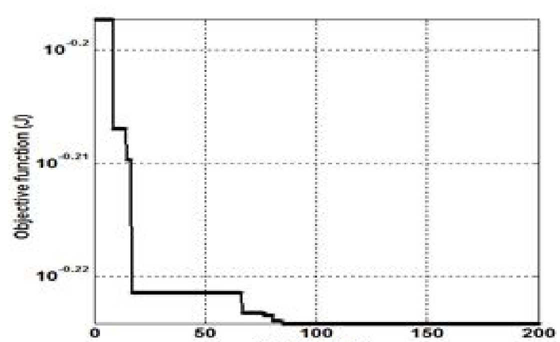

Fig. 7 Convergence of the objective function for gbest

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VI. Conclusions

The investigation in this paper illustrated two novel uses of TCSC in a multimachine power system. The TCSC has been installed for both dynamic and steady state secure operation of the power system. The optimal location of the TCSC has been determined based on small signal stability improvement in order to achieve dynamic stability. TLF sensitivity based load curtailment method has been used also to constrain line flow congestion. A new stochastic optimization technique, PSO algorithm, has been implemented for optimal parameter setting and identification of the optimal site of TCSC controller by minimizing the desired objective function. It has been revealed that the proposed approach can provide both economic and secure operating conditions to the power system.

Appendix A

A.1 Power flow result at base load

TableA.I. Base case power flow

Load Bus	Real Load (P_L) (MW)	Reactive Load (Q_L) (MW)	Line	Power Flow (S) (MW)
4	0	0	# 4(4-5)	32.35
5	125	50	# 5(4-6)	25.33
6	90	30	# 6(5-7)	-79.38
7	0	0	# 7(6-9)	-55.65
8	100	35	# 8(7-8)	72.64
9	0	0	# 9(8-9)	-20.28

A.2 Transmission Line Flow (TLF) Sensitivity and load curtailment

1) Without TCSC: TLF sensitivity for a congested line #4 (4-5) due to change load power at bus 5

$$\Delta S_{ij} = (85.44\text{-}32.35) = 53.09 \text{ MW}$$

$$\Delta P_k = (187.5\text{-}125.0) = 62.5 \text{ MW}$$

$$T_{ij}^{k} = \frac{53.09}{62.5} = 0.8494;$$

$$\sum_N T_{ij}^{k} = T_{45}^{5} + T_{46}^{5} + \cdots\cdots + T_{89}^{5} = 0.7659$$

$$S_{ij} = 85.44 \text{ MW and } \overline{S_{ij}} = 70 \text{ MW}$$

$$\overline{\Delta S_{ij}} = (85.44\text{-}70.0) = 15.44 \text{ MW}$$

The amount of load curtailment at bus 5 is thus obtained

as $$P_k^{cut} = \frac{0.8494}{0.7659} \times 15.44 = 17.12 \text{ MW}$$

2) With TCSC installed in line # 7*(*6-9*):* TLF sensitivity of the congested line #4 (4-5) due to change load power at bus 5

$$\Delta S_{ij} = (78.11\text{-}32.35) = 45.76 \text{ MW}$$

$$\Delta P_k = (187.5\text{-}125.0) = 62.5 \text{ MW}$$

$$\sum_N T_{ij}^{k} = T_{45}^{5} + T_{46}^{5} + \cdots\cdots + T_{89}^{5} = 0.4662.$$

$$T_{ij}^{k} = \frac{45.76}{62.5} = 0.7321;$$

$$\overline{\Delta S_{ij}} = (78.11\text{ -}70.0) = 8.11 \text{ MW}$$

The amount of load curtailment at bus 5 is now

$$P_k^{cut} = \frac{0.7321}{0.4662} \times 8.11 = 12.73 \text{ MW}$$

Improvement of load curtailment

$$= \frac{17.12 - 12.73}{17.12} = 25.64\%$$

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